Final Report for contract number N00014-89-J-1427, "Acoustical Cues for Sound Localization", January 1, 1989 to December 31, 1993

The Specific Aims of the contract were: 1) Characterize the acoustical cues for sound localization; and 2) Measure the accuracy with which human subjects localize broad- and narrow-band sound presented at unknown horizontal and vertical locations. The results of research supported by that contract have been published or are in press as eight research articles in peer-reviewed journals, one review article, one book chapter, and six abstracts. References are given below.

In regard to the first aim, we have developed efficient methods for recording the transfer function of the human ear. Currently, we can measure the transfer functions of a subject's two ears for 360 sound source locations in about eight minutes. The ease of this measurement procedure makes it possible to record transfer functions for every subject who participates in behavioral experiments, thus making it possible to link aspects of behavior to characteristics of individual subjects' acoustical cues. We have reported the directionality of the external ear in regard to sound pressure [1] and interaural delay [2]. Depending on the sound frequency, the directional pattern of the ear for sound levels contains either one or two areas of maximal sensitivity. Single maxima can be located to the subject's side (e.g., typically observed for 6 and 10 kHz) or straight ahead (e.g., 14 kHz). Double maxima can be separated vertically (e.g., 8 kHz) or horizontally (12 kHz). The patterns of directionality are fairly constant across subjects, with the proviso that a particular spatial pattern that is observed at one frequency for one subject might be observed at a different, nearby frequency for a different subject. We hypothesized that the spatial dependence of interaural delays at frequencies above about 4 kHz might be much more complex than is observed at lower frequencies because of the filtering properties of the external ears at high frequencies. We confirmed that hypothesis for extremely narrow bands of frequency (essentially, single spectral lines). Subjects can use interaural delays as sound localization cues only in the form of envelope delays, however, and envelope delays are meaningful only within a bandwidth that is at least as wide as a psychophysical critical band. Within critical bandwidth signals, we found that the spatial dependence of envelope delays is much like that seen for pure tones at low frequencies.

In regard to the second aim, we have conducted behavioral studies of broadband and narrowband localization by normal listeners and broadband localization by monaural patients. Normal subjects localized broadband noise in azimuth and elevation [3]. We developed a response protocol in which subjects reported the locations of sounds by orienting with the head. We used an electromagnetic device to track the head orientation. The main advantage of this protocol over methods that had been used previously was that subjects were free to point to any location in azimuth and elevation. That is, there was no need to restrict stimuli to a single plane or to force responses to correspond to particular discrete locations. Localization accuracy, as expected, was best in the front half of space, with average error magnitudes of 5.8° in the horizontal and 5.7° in the vertical dimension. Near the vertical midline, horizontal localization was more accurate than vertical localization, but the opposite was true for lateral locations. That study of broadband localization provided useful baseline data for studies of human localization.

We studied localization of broadband sounds by monaural subjects [7] in order to test the accuracy of localization in the absence of interaural difference cues, i.e., localization using spectral shape cues alone. Most previous studies of localization in the absence of interaural difference cues have worked with normal-hearing subjects who wore an earplug in one ear. Unfortunately, the unilateral earplug, by introducing an interaural level difference, results in a pronounced displacement in responses directed toward the side of the open ear. We attempted to circumvent that problem by studying localization in patients that were unilaterally deaf from birth. Two of the five patients showed performance that was indistinguishable from control subjects who wore unilateral earplugs. All of their responses showed a displacement toward the side of the normal-hearing ear, and they seldom oriented to the impaired side. In contrast, the remaining three patients showed remarkably accurate localization. Although their performance was statistically less accurate than normal binaural controls, these patients showed no consistent displacement toward the normal-hearing side, and they localized targets on the hearing and on the impaired sides about equally well. The performance of these latter patients demonstrates that spectral shape cues can provide useful spatial information in the horizontal as well as the vertical dimension.

We used narrowband sounds to probe the mechanisms by which subjects utilize spectral shape cues for localization [6]. Stimuli were bandpass filtered, with bandwidths of 1/6 octave and center frequencies of 6, 8, 10, and 12 kHz. Subjects made conspicuous errors in localization in the vertical and front/back dimensions. A given subject tended to localize all sounds of a particular center frequency within a particular restricted vertical and front/back region. The regions that contained subjects' responses varied with subject and with stimulus center frequency. Despite the vertical and front/back errors, however, localization in the lateral dimension was almost equally accurate for narrowband and broadband stimuli. The accurate performance in the lateral dimension suggested that these binaural subjects accurately utilized the information provided by interaural differences in sound pressure level. The subjects' performance in the vertical and front/back dimensions could be attributed to characteristics of the directional transfer functions (DTFs) of the subjects' external ears. The DTFs corresponding to the response regions tended to contain spectral features, including peaks and steep slopes, that resembled features of the narrowband stimuli. We measured the correlations between stimulus spectra and the DTFs that corresponded to 1652 locations around the subject. The regions in which subjects responded tended to have DTFs that correlated most closely with the stimulus spectra. We developed a computational model that used the given subject's external ear DTFs to predict his or her narrowband localization performance. The model incorporated interaural level difference and spectral correlation cues. The model was remarkably successful in predicting the performance of our subjects in localizing narrowband stimuli, and it generalized readily to predict localization of a variety of types of stimuli.

In behavioral studies, we found substantial differences between subjects that, to a large extent, could be accounted for by differences in the properties of their DTFs. In bioacoustical studies, we made preliminary observations suggesting that the majority of inter-subject differences in DTFs could be eliminated by shifting the DTFs in frequency. Inter-subject differences in DTFs

and behavior, as well as their relationship to virtual acoustics, are the topic of a new contract submitted to the ONR.

PUBLICATIONS

Peer-Reviewed Research Articles:

1. MIDDLEBROOKS, J. C., J. C. Makous, and D. M. Green (1989) Directional sensitivity of sound pressure levels in the human ear canal. J. Acoust. Soc. Am. 86:89-108.

2. MIDDLEBROOKS, J. C., and D. M. Green (1990) Directional dependence of interaural envelope delays. J. Acoust. Soc. Am. 87:2149-2162.

3. Makous, J. C., and J. C. MIDDLEBROOKS (1990) Two-dimensional sound localization by human listeners. J. Acoust. Soc. Am. 87:2188-2200.

4. MIDDLEBROOKS, J. C., and D. M. Green (1992) Observations on a principal components analysis of head-related transfer functions. J. Acoust. Soc. Am. 92:597-599.

5. Zhou, B., D. M. Green, and J. C. MIDDLEBROOKS (1992) Characterization of external ear impulse responses using Golay codes. J. Acoust. Soc. Am. 92:1169-1171.

6. MIDDLEBROOKS, J. C. (1992) Narrowband sound localization related to external ear acoustics. J. Acoust. Soc. Am. 92:2607-2624.

7. Slattery, William H. III, and J. C. MIDDLEBROOKS (1994) Monaural sound localization: Acute versus chronic unilateral impairment. Hearing Res. (in press).

8. MIDDLEBROOKS, J. C., A. E. Clock, L. Xu, and D. M. Green (1994) A panoramic code for sound location by cortical neurons. Science (scheduled to appear in May 6, 1994 issue).

Book Chapters and Reviews:

9. MIDDLEBROOKS, J. C., and D. M. Green (1991) Sound localization by human listeners. Ann. Rev. Psychol. 42:135-159.

10. MIDDLEBROOKS, J. C. (1994) Spectral shape cues for sound localization. in Binaural and Spatial Hearing (Gilkey and Anderson, eds.), (in press)

Abstracts:

11. MIDDLEBROOKS, J. C. (1990) Two-dimensional localization of narrowband sound

sources. Abst. Assoc. Res. Otolaryngol. 13:109.

12. MIDDLEBROOKS, J. C. (1991) Narrowband sound localization related to acoustical cues. IEEE ASSP Workshop on Applications of Signal Processing to Audio and Acoustics., New Paltz, N.Y., pp 2.5.

13. Slattery, W. H., and J. C. MIDDLEBROOKS (1992) Monaural sound localization: acute vs. chronic unilateral impairment. Abst. Assoc. Res. Otolaryngol. 15:95.

14. MIDDLEBROOKS, J. C., A. E. Clock, and D. M. Green (1993) Sound localization represented in the firing patterns of auditory cortical neurons. Neurosci. Abst. 19:1688.

15. Clock, A. E., L. Xu, and J. C. MIDDLEBROOKS (1994) Neural network analysis of auditory spatial representation: I. Temporal firing patterns of cortical neurons independent of stimulus duration.

16. Xu, L., A. E. Clock, and J. C. MIDDLEBROOKS (1994) Neural network analysis of auditory spatial representation: II. Spatial interpolation and level invariance. Abst. Assoc. Res. Otolaryngol. 17.